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**ALUMINUM POWDER/WATER REACTION
IGNITED BY ELECTRICAL PULSED POWER**

BY W. M. LEE

WEAPONS RESEARCH AND TECHNOLOGY DEPARTMENT

12 AUGUST 1993



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NAVAL SURFACE WARFARE CENTER
DAHLGREN DIVISION • WHITE OAK DETACHMENT

Silver Spring, Maryland 20903-5640

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FOREWORD

This work was performed for the Office of Naval Technology, Code 23 (now the Office of Naval Research, Code 4525), as part of the Explosives Thrust within the Explosives and Undersea Warheads Block Program, PE 62314. The results and conclusions presented will be of interest to those seeking information on the reactivity of aluminum powder/water mixtures activated by electrical pulses.

The author wishes to acknowledge the contributions of the following personnel: continuing encouragement and support by Dr. R. M. Doherty and Mr. L. A. Roslund, pulsed power technical help by Mr. H. B. Hall, gas analysis by Mr. D. W. Carlson, and provision of the pulsed power facility by Dr. R. E. Meger at the Naval Research Laboratory.

Approved by:

Kurt F. Mueller

KURT F. MUELLER, Head
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ABSTRACT

The effectiveness of the electrical pulsed power technique in driving aluminum-water reactions has been studied. The reactant was prepared by mixing, in the stoichiometric ratio, fine aluminum powder (the fuel) and water (the oxidizer). The electrical energy was delivered to the reactant through an ignition wire embedded in it. The primary objective of the study was to maximize the energy efficiency, which is defined as the ratio of the chemical energy output from the reaction to the electrical energy input. The energy efficiency depends critically on the electrical circuit parameters, physical parameters of the metal fuel powder, and geometrical arrangements of the reactant. Under an optimized set of experimental variables, the energy efficiency exceeds 100.

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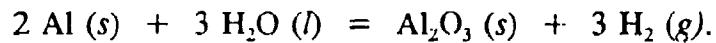
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CHAPTER 1

INTRODUCTION

Without counting the weight of water that should be available in most Navy environments, the energy density of reactive metal/water systems, either gravimetric or volumetric, exceeds that of conventional high explosives as seen in Table 1-1. The reaction with water of the reactive metals -- such as aluminum, magnesium, lithium, beryllium, and titanium -- is represented by the following equation in which aluminum is selected as the metal.



But to react with water, most reactive metals have to be activated, usually by the energy output of other energetic materials as exemplified in aluminized explosives or propellants.

TABLE 1-1. HEAT OF REACTION FOR SOME METAL/WATER REACTIONS

Metal	Gravimetric (kcal/g)	Volumetric (kcal/ml)
Be	8.62	16.0
B	4.50	10.5
Al	3.61	9.75
Mg	3.12	5.42
Li	7.59	4.03
Ti	1.70	7.66
PBXN-103	2.20	4.1

Since 1987, under the sponsorship of the Office of Naval Technology (ONT, now the Office of Naval Research [ONR-T]), a different approach has been taken to activate reactive metal fuels, especially aluminum.¹⁻⁵ The primary purpose for this new approach is to develop totally insensitive underwater weapon systems. Aluminum fuel is activated by ohmic heating when an electric current pulse passes through it. Fast electrical activation of the reactive metal conductor in a water environment ignites and sustains the metal/water reaction that in turn generates hydrogen gas and thermal energy. However, the surrounding water, besides its role as the oxidizer, acts as a heat sink to quench the burning metal. Thus the activation of the metal fuel to such a degree that it fully reacts with the surrounding water requires substantial energy. If the activation of the metal fuel solely depends on electrical energy, the physical size of the electrical power source needed will make the reacting system impractical for any underwater application. Thus the success of the metal/water electrical pulsed power system for a new generation of Navy underwater munitions critically depends on reducing the amount of electrical energy the system requires. Previous investigations^{1,2,4} on aluminum/water reactions showed that the electrical energy input for activation can be reduced by incorporating various experimental techniques. The techniques include alloying of aluminum by lithium, multiple-pulse application, and premixing the metal powder with water. The common goal of these methods is to improve the energy efficiency of the reaction, defined as the ratio of the chemical energy output to the electrical energy input.

Among these methods, the premixing technique is particularly attractive for its high energy efficiency. It is also assumed that the needed water for mixing can be supplied from an external source at any time. This method utilizes only the stoichiometric amount of water that is to be mixed with the metal fuel before the electrical activation. Thus it alleviates a fast quenching of the burning metal manifested in the case where the activated metal fuel is dumped into a large water pool. In this method, the role of the electrical energy input is to ignite the reactants, consisting of the metal powder and water, by exploding a small mass of a conductor placed in the mixture. The conductor, normally in the shape of wire or foil, can be any material as long as it explodes readily upon electrical pulse application. Once the reactants are ignited, the chemical energy produced from the reaction continuously activates the metal fuel so that the reaction is sustained to completion. This investigation focuses on how to maximize the energy efficiency when the premixing method is employed. In Chapter 2, the principle of the electrical activation is described in more detail. The experimental methods employed in this investigation are presented in Chapter 3. The details of the experimental results are presented in Chapter 4, emphasizing the effect of various system parameters on the energy efficiency. Conclusions and recommendations for future work are given in Chapter 5.

CHAPTER 2

BASIS OF ELECTRICAL ACTIVATION

Solid metal fuels like aluminum, when activated by a high-power electrical pulse, undergo a rapid chemical reaction with water to form a metal oxide and hydrogen gas. This activation by ohmic heating is crucial to overcoming the impediment to the reaction caused by the rapid formation of a protective oxide layer on the metal surface. This impediment is particularly significant when the activated metal fuel is in contact with a large water pool acting as a heat sink. For the metal fuel to completely react with water, it needs to be activated almost to full vaporization, the state in which the metal is dispersed within the water on an atomic scale and not affected by the heat loss to the surrounding water. The electrical energy expended to activate aluminum to such a state is approximately 10 kJ per gram of the metal. The reaction in turn releases 15 kJ, the heat of the reaction. Due to the inherent time lapse for transport of the water molecules and for the chemical interaction of the reacting molecules, completion of the chemical reaction lags behind the electrical explosion of the metal conductor triggered by the pulse. An increase in the pulsed power can narrow the time gap (the time difference between the two peaks) shown in Figure 2-1.

When an electrical pulse goes through the reactive metal placed in water, the activation of the metal is greatly affected by the nature of its interaction with water, both physically and chemically. As the solid metal melts, it not only physically disintegrates but also chemically reacts with the water to produce the metal oxide. Consequently, the conducting path witnesses a steep increase in the electrical resistance that accelerates the rate of electrical energy dissipation. The large water pool, despite its adverse role in quenching the hot metal to suppress the chemical reaction, actually helps increase the electrical resistance by absorbing the heat generated electrically and chemically. The accelerated dissipation of the electrical energy triggers the explosion. The use of the stored electrical energy for igniting the chemical reaction of the metal conductor with the water will be most efficient if the conductor carries the current to near its peak value with little loss and explodes immediately.¹ Up to the peak current time, the circuit parameter including the physical dimension of the conductor should satisfy the oscillatory discharge ($R < 2 (L/C)^{1/2}$) of a capacitor bank. Under this condition, the capacitive energy is transformed to inductive energy at the peak current time, and the inductive energy can be dissipated effectively during the explosion since it is not subject to the voltage drop across the dissipating medium.

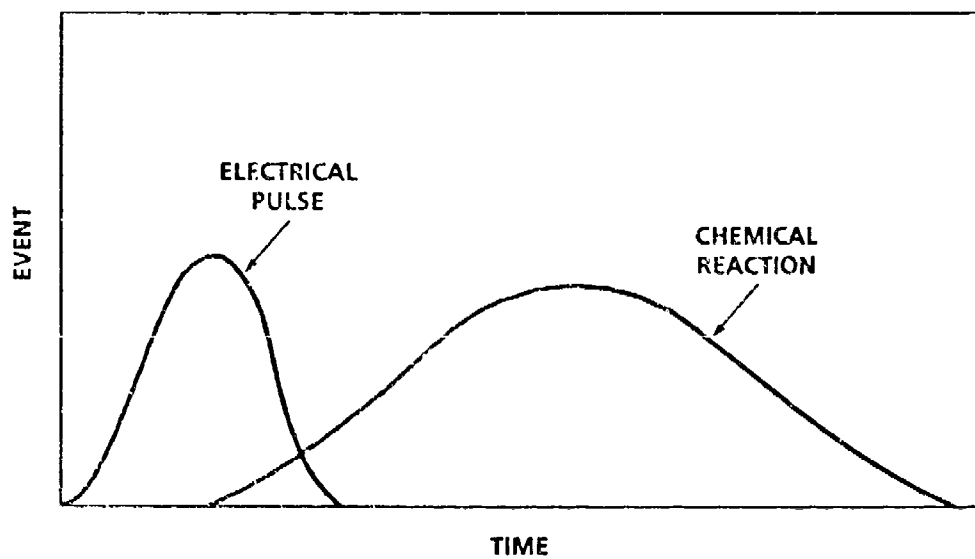


FIGURE 2-1. TIME CORRELATION OF ELECTRICAL EXCITATION AND
CHEMICAL REACTION

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If the activation of the metal fuel depends solely on ohmic heating and the system in which it is to be used is volume limited, the size of the electrical energy storage unit needed to activate a large amount of the fuel will be too bulky. Thus, it is necessary to employ means other than ohmic heating in order for the pulsed power technique to have practical value for inducing the metal/water reaction. One way to reduce the energy required for the activation of the metal is to minimize heat loss to the large water pool. The energy required to initiate the metal-water reaction can also be reduced if the metal is already disintegrated into fine particles even before the activation process. Such conditions can be met if fine metal particles mixed with the stoichiometric amount of water are used as the reactants. The ignition is accomplished by exploding a conductor embedded in the mixture. The temperature at the zone around the exploding conductor should be high enough to ignite the reaction in the mixture. Once ignited, the thermal energy produced from the chemical reaction will be sufficient to sustain the reaction to completion.

The success of the scheme described above depends on maintaining a sufficient reacting system temperature so that the formation of aluminum oxide does not prohibit the advance of the reaction. Thus, we can hypothesize a threshold temperature below which the reaction is not sustained to completion. Maintenance of the threshold temperature depends on several factors. First, during the ignition of the mixture by the electrical pulse, the chemical reaction should be advanced to such an extent that, even after the termination of the pulse, the chemical energy is high enough to drive the reaction to completion. The larger the overlap of the events, the more easily the reactants can attain the threshold temperature. Second, once ignited, the chemical reaction must proceed fast enough to maintain the threshold temperature. Third, the quenching of the reaction should be minimized by using the stoichiometric amount of water and physically confining the reaction space.

The above requirements can be met by controlling many aspects of the reacting system, grouped largely into electrical and nonelectrical parameters. Electrical parameters include mainly the pulse shape determined by the pulse-forming circuitry, while nonelectrical parameters include the physical and chemical properties of the metal fuel and geometric arrangement of the reactants. In this investigation, the effect of these parameters on igniting the chemical reaction is quantified by determining the energy efficiency. The efficiency is defined by the ratio of the chemical energy output to the electrical energy input.

CHAPTER 3

EXPERIMENTAL PROCEDURES

The electrical circuit used in the present work is shown in Figure 3-1. The medium that dissipates the electrical energy consists of a conducting wire placed along the center axis of a cylindrical reaction chamber filled with a stoichiometric mixture of deionized water and aluminum powder. Metal-powder particle size, spherical or non-spherical, ranges from 20 to 350 μm in average diameter (Alfa Products, 99.5%). The typical weight of the mixture prepared in the tests was 20 to 45 g. After the aluminum powders and water were mixed, a small amount (less than 2 wt% of the mixture) of an alumina fiber bundle (Saffil, manufactured by ICI, Inc.) was added to secure uniform distribution of the powder throughout the water. Aluminum or copper wire was used as the conducting wire, which weighed less than 3% of what the powder weighed. The mixture and the wire were placed in a polyethylene cartridge with a brass electrode at each end (Figure 3-2). One electrode was also used as a diaphragm that ruptured when the pressure inside the cartridge reached a certain value. The cartridge was placed inside a steel pressure chamber and proper electrical connections were made between the units. At the diaphragm end of the pressure chamber, a 23-l collection chamber was attached in order to collect the product gas from the metal/water reaction. A variant of this configuration was made by placing an intermediate chamber filled with the metal/water mixture between the pressure and collection chambers as seen in Figure 3-3. The cartridge of the primary chamber was 5 inches high and 0.625 inch in diameter. The volume of the secondary chamber was 30-50% that of the primary chamber.

The collection chamber was under vacuum before the pulse was applied to the reactants. The product gas pressure in the collection chamber was monitored using a pressure transducer (Robinson-Halpern Model 153), and the product gas was analyzed using gas chromatography. In most tests, the product gas was more than 95 mol% hydrogen.

A current transformer (Pearson 301X) and a resistive divider were used to measure the current through the reactants and the voltage developed across them, respectively. The voltage of a capacitor bank ($C = 600 \mu\text{F}$) was adjusted between 2.5 and 4.5 kV. The current, voltage, and pressure were recorded as functions of time with both analog and digital (Norland, Model Prowler) oscilloscopes.

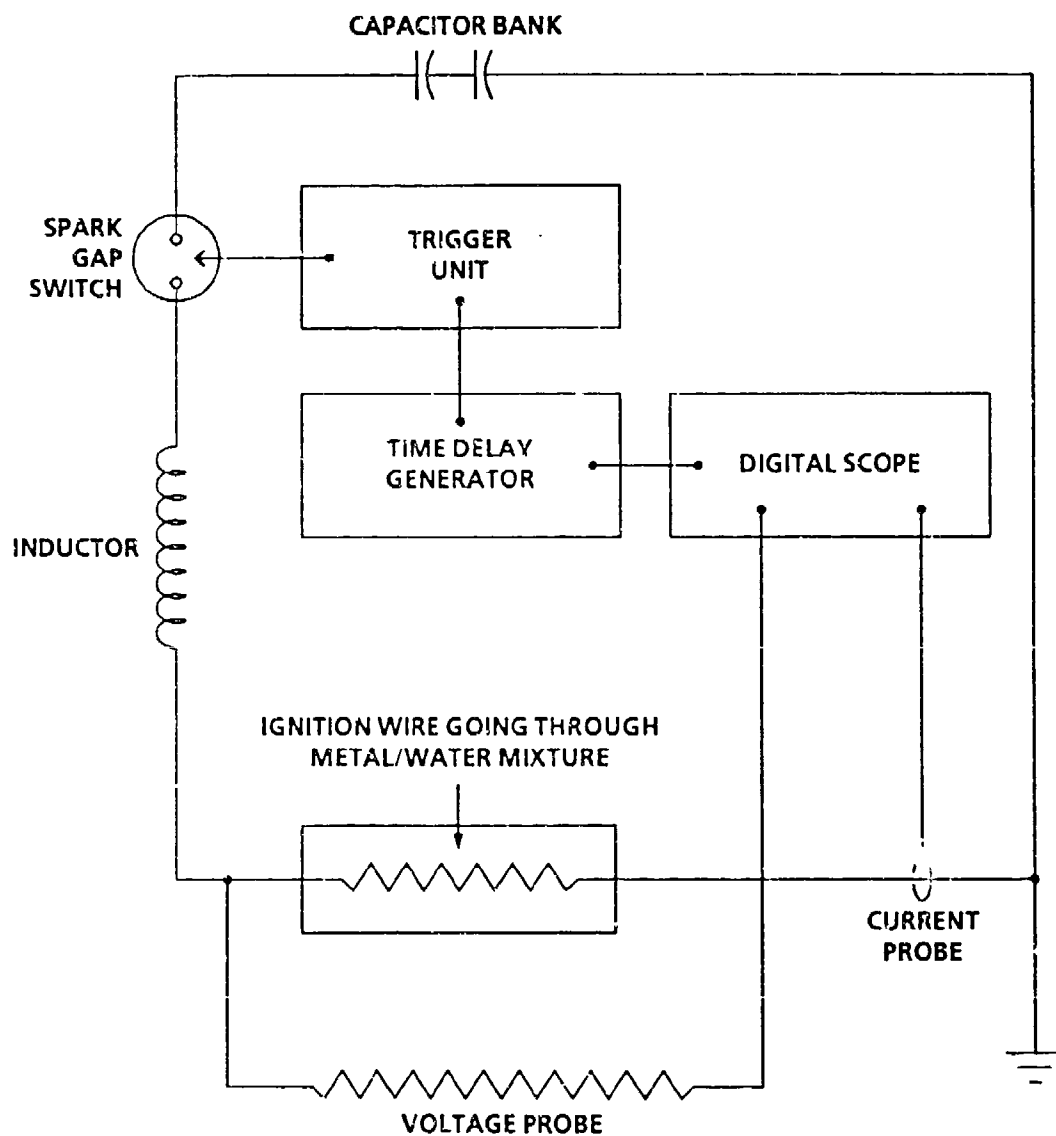


FIGURE 3-1. ELECTRICAL CIRCUIT FOR THE TEST

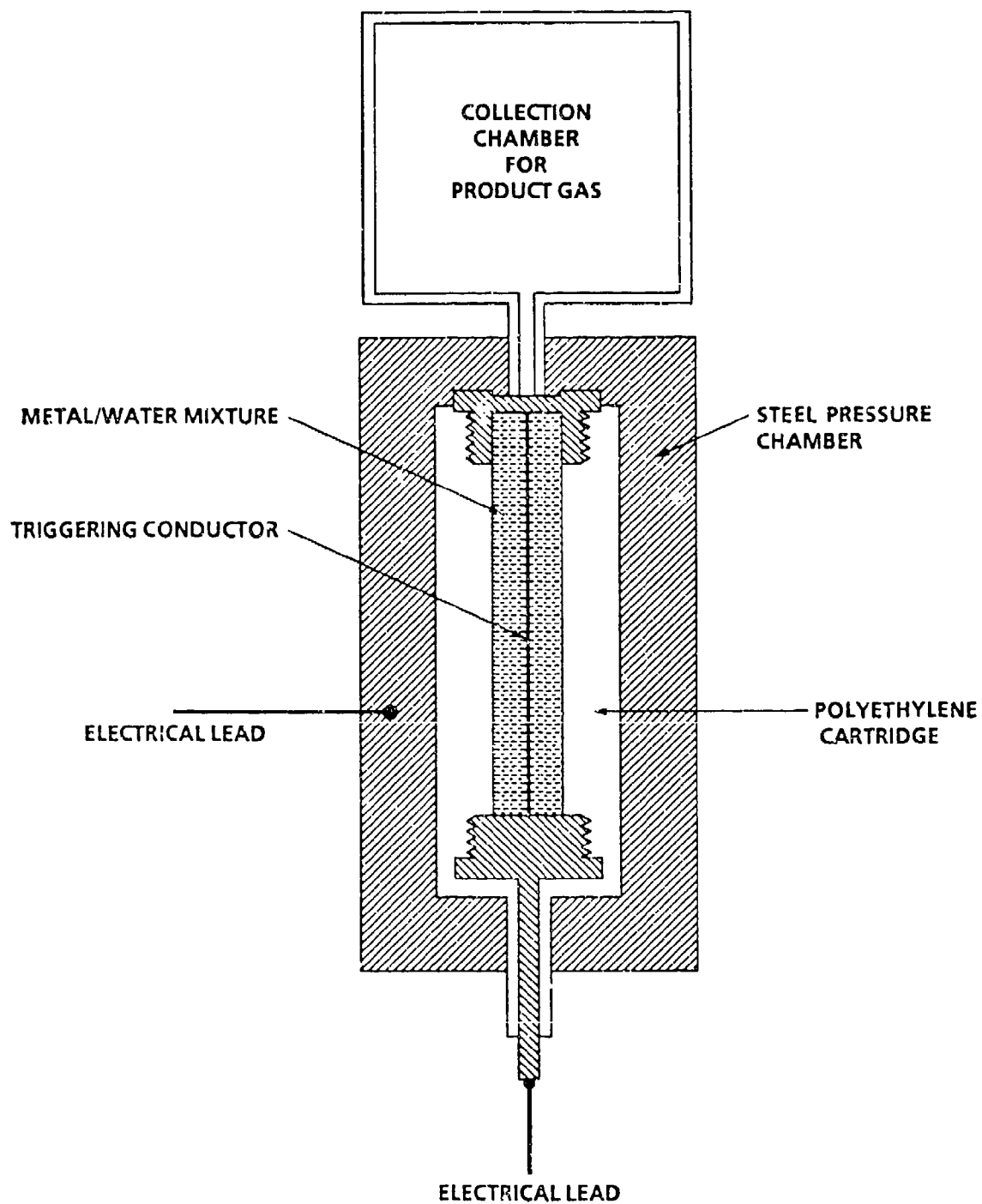


FIGURE 3-2. COLLECTION OF PRODUCT GASES

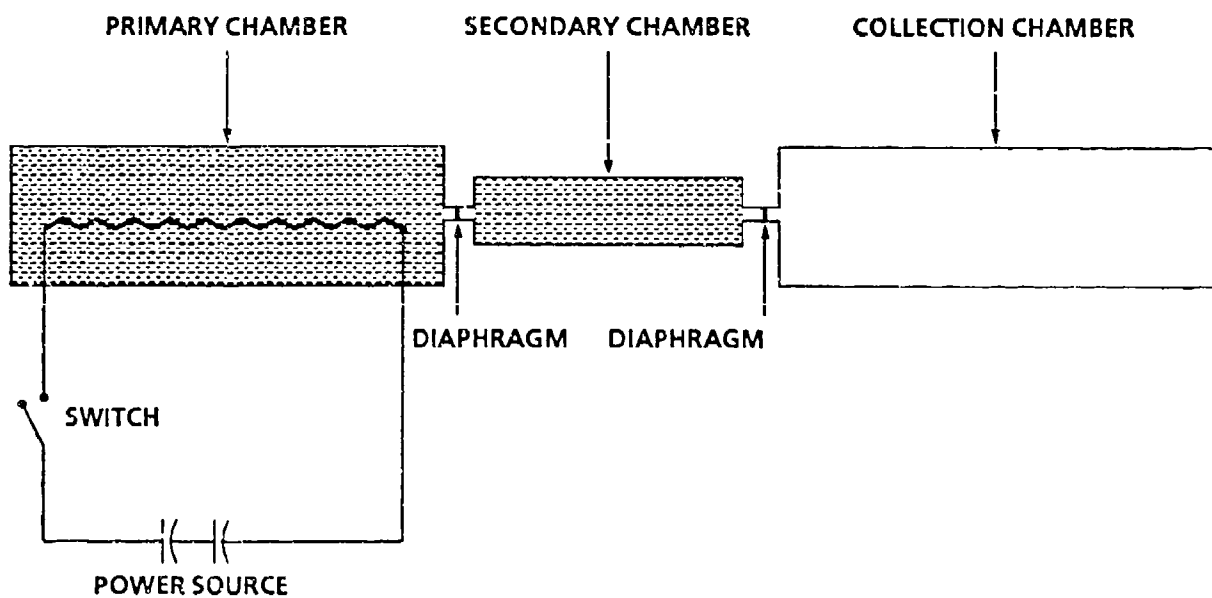


FIGURE 3-3. INSERTION OF SECONDARY REACTION CHAMBER BETWEEN PRIMARY REACTION CHAMBER AND COLLECTION CHAMBER

CHAPTER 4

RESULTS AND DISCUSSION

ADJUSTMENT OF ELECTRICAL PARAMETERS

The shape of the current trace of an exploding aluminum wire residing in an Al/H₂O slurry is determined by the physical dimensions of the wire and the nature of the interaction between the wire and the surrounding medium when other circuit parameters are kept constant. Table 4-1 shows the effect of the cross-sectional area of the wire on the energy efficiency, and Figure 4-1 shows the current density as a function of time for several cross sections of the wire. In Figure 4-2, the

TABLE 4-1. EFFECT OF THE CROSS SECTION OF THE IGNITION WIRE ON THE ENERGY EFFICIENCY

The cross section and the length of the mixture (16 g of aluminum and 16 g of water) are 1.98 cm² and 11 cm, respectively, and $L = 20 \mu\text{H}$, $V_c = 4 \text{ kV}$.

Cross Section (10 ⁻² mm ²)	Electrical Energy Input, E_i (kJ)	Percentage of the Mixture Reacted	Chemical Energy Output, E_o (kJ)	Ratio of E_o to E_i
5	4.8	19	46	9.5
32	4.8	75	180	38
63	4.8	72	173	36
95	4.8	82	197	41
127	4.8	77	185	39
158	4.8	12	28	5.8

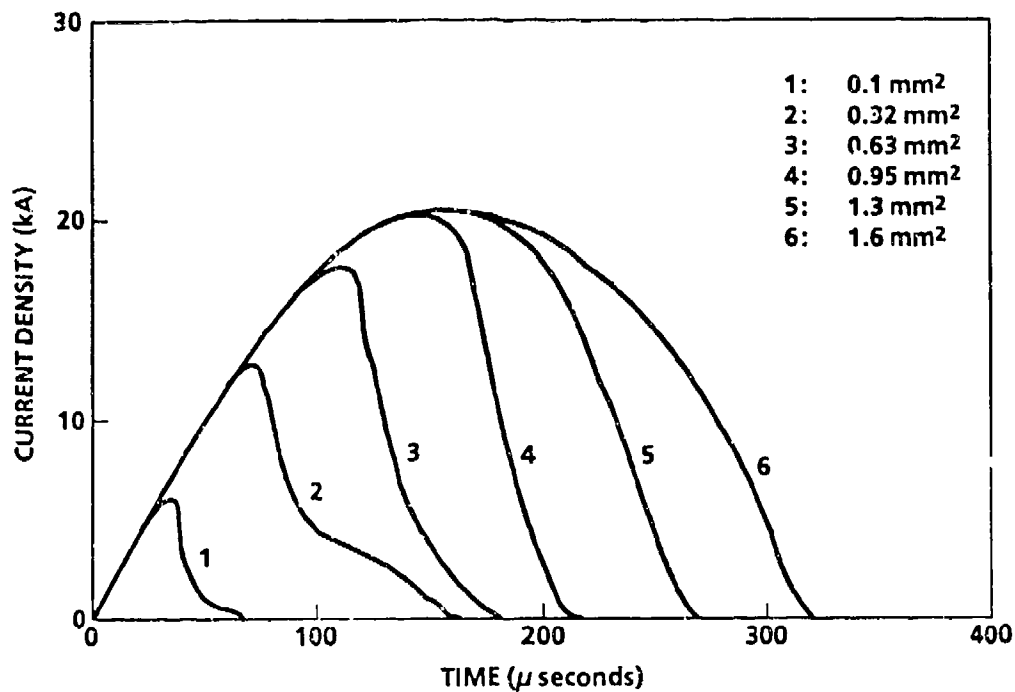
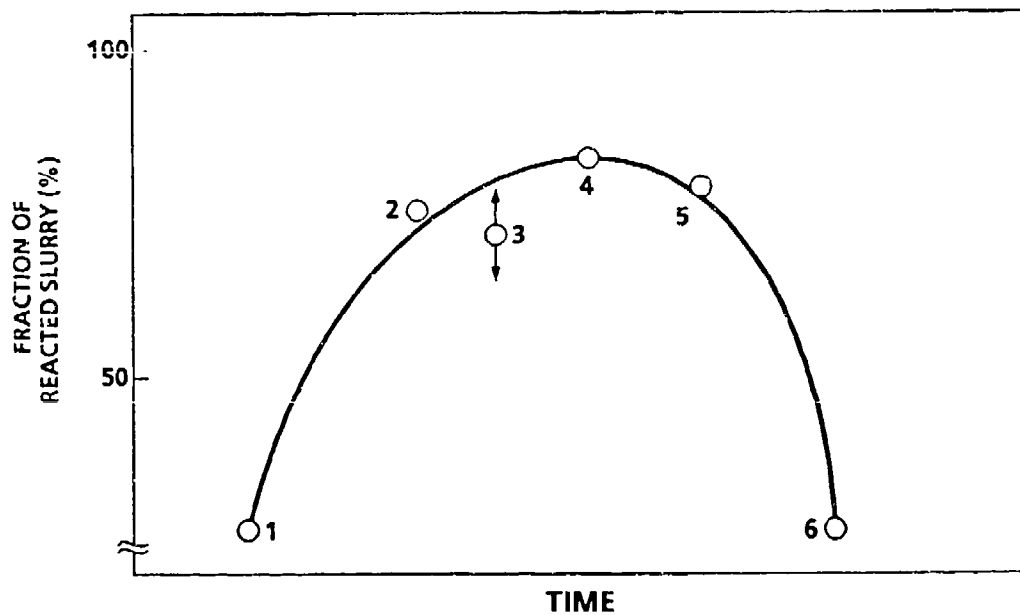


FIGURE 4-1. CURRENT TRACE AS A FUNCTION OF THE CROSS-SECTIONAL AREA OF THE IGNITION WIRE



Note: The abscissa of each point is represented by 90% of the discharge time of the corresponding curve in Figure 4-1.

FIGURE 4-2. EXTENT OF THE CHEMICAL REACTION AS A FUNCTION OF THE CROSS-SECTIONAL AREA

percentage of the slurry that underwent the reaction is plotted as a function of the wire cross section. The smaller the wire diameter, the earlier the wire explodes, resulting in less energy being dissipated through the medium. The total dissipated energy increases with wire diameter up to a cross section of 0.95 mm^2 . At this cross section, the near-peak current explosion mentioned in the previous chapter is satisfied. The power curves corresponding to Figure 4-1 also show that the maximum power is obtained when the wire cross section is 0.95 mm^2 . It is reasonable to assume that the efficiency of the wire in igniting the reaction depends on the local temperature created by the exploding wire. The local temperature should be a function of both the total dissipated energy and the rate of dissipation (power).

The thermal energy generated by the dissipation of electrical energy in a pulsed form heats the region around the wire through conduction, radiation, and shock-wave impact. Any mode of this thermal energy dissipation should follow closely the real time power curve. Indeed, the measurements of the shock-wave pressure show that it directly reflects the power curve.³ Thus, it is quite obvious that the compressed dissipation of a larger electrical energy, manifested in the case of the wire with a cross section of 0.95 mm^2 , should impart more thermal energy to the surroundings of the exploding wire.

We can also regard the igniting wire as a mere energy converter. At a given set of circuit parameters, the converter transforms the stored electrical energy into thermal energy in a pulsed form whose amplitude and duration depend on the wire diameter. The most efficient converter dissipates the stored energy with minimum loss up to near the peak current time and, immediately after this point, dissipates the energy in the shortest possible time. This condition can be met, as explained in Chapter 2, if the wire explodes at very near the peak current whose value and time are determined by the oscillatory condition of a capacitor discharge. It is interesting to see that the power of inductive stored energy in triggering the metal/water reaction applies to the slurry system in exactly the same manner as shown in the exploding wire in water.¹

Based on the reasons presented above, it is easy to see why the wire of smallest diameter does not have much igniting power. It cannot deliver the required power due to premature explosion. The wire of large diameter, on the other hand, cannot dissipate the energy fast enough due to the higher conductivity. There exists a certain wire diameter or a range of diameters that can, upon explosion, initiate the slurry reaction effectively. The results shown in Figure 4-2 support this point.

Thus far, other circuit parameters such as inductance and capacitance have been fixed during the optimization of the wire parameters. However, another key variable to consider in creating the electrical pulse is the pulse width, which is most effectively adjusted by varying the inductance of the circuit. To compare the effect of the pulse width on the energy efficiency, the following conditions must be satisfied: the total

dissipated energy is constant regardless of the pulse width and the condition of the peak current explosion needs to be satisfied. These conditions can be met by varying the circuit parameters, mainly the inductance and, to a lesser extent, the capacitance and the wire parameters. Now the question is whether there is a range of pulse widths that efficiently ignites the reaction.

The power traces satisfying the conditions described above are shown in Figure 4-3. The pulse width is mainly adjusted by varying the circuit inductance. In addition, for either the very short pulse or the very long pulse, the capacitance and the wire diameter were varied. Generally, the smaller the inductance, the sharper the energy dissipation rate. The effect of the pulse width on the energy efficiency is shown in Table 4-2 and Figure 4-4. The energy efficiency drops sharply as the pulse width becomes shorter. It is likely that most of the stored energy in this case is converted into mechanical energy in the form of a shock-wave. Then the slurry system does not have any induction time during which it receives a critical thermal energy from the exploding wire necessary to ignite the reaction.

Decreases in the efficiency for the longer pulse may be explained by the following factors. First, the large inductor has a higher ohmic energy dissipation, utilizing less of the primary energy for activating the reacting medium. Second, the longer pulse has a lower rate of energy dissipation and thus does not create the critical local temperature around the igniting wire.

The questions regarding the effect of the pulse width can be best answered by using a constant current source of varying magnitude. By adjusting the duration and the magnitude of such current applied to the reacting medium, the effect of pulse shape on the triggering efficiency will be clearly manifested.

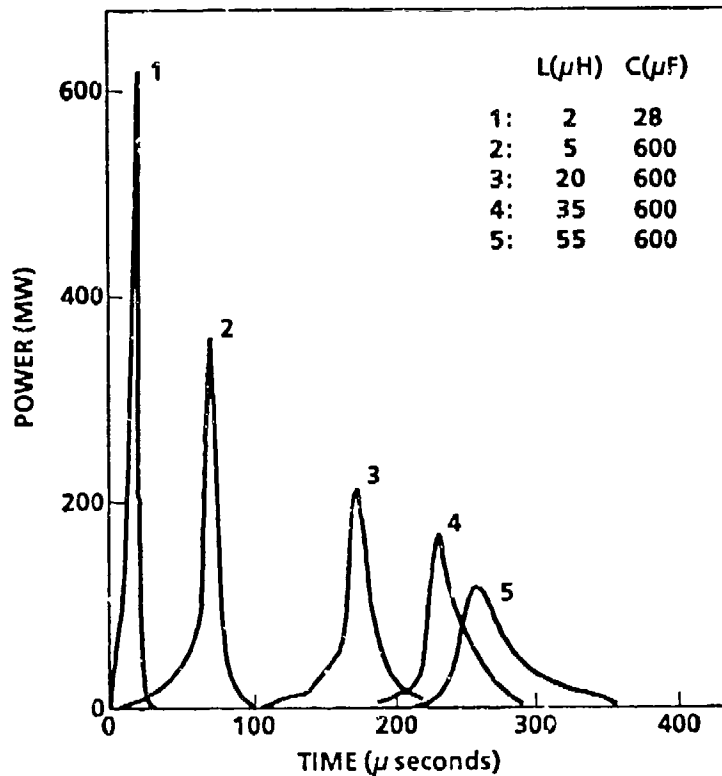
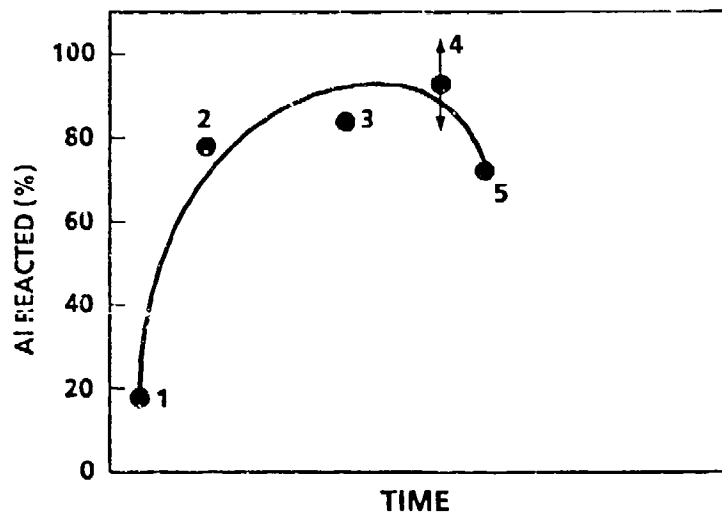


FIGURE 4-3. DISSIPATION OF THE STORED ELECTRICAL ENERGY THROUGH THE IGNITION WIRE IN VARIOUS PULSE WIDTHS



Note: The abscissa of each point is represented by the peak power time of the corresponding curve in Figure 4-3.

FIGURE 4-4. EXTENT OF THE CHEMICAL REACTION AS A FUNCTION OF THE PULSE WIDTH

TABLE 4-2. EFFECT OF THE ELECTRICAL PULSE WIDTH ON THE ENERGY EFFICIENCY

The Al/water mixture contains 16 g of aluminum powder and 16 g of water.

L (μ H)	C (μ F)	V _c (kV)	E _i (kJ)	Percentage of the Mixture Reacted	E _o (kJ)	Ratio of E _o to E _i
2	28	18	4.5	29	69	15
5	600	4	4.8	77	185	39
20	600	4	4.8	82	197	41
35	600	4	4.8	88	211	44
55	600	4	4.8	66	158	33

EFFECT OF GEOMETRIC ARRANGEMENTS OF THE REACTANTS ON THE ENERGY EFFICIENCY

From the peak current explosion requirement discussed in the previous section, the optimum cross section of the ignition wire can be determined for a given primary energy since the cross section and the thermal properties of the wire determine the time of the explosion. The wire length should then fall within a certain range. If the wire is longer than the upper limit, the oscillatory condition mentioned in the previous section will not be satisfied (or the wire will not be able to carry the current to the peak value). If the wire length is too short, the end effect due to the higher resistance between the wire and the electrical port will dominate.

The energy efficiency shown in the previous section was obtained at a particular wire length (around 4 inches). It is interesting to ask whether the efficiency depends on the wire length with the fixed cross section as long as it falls within the proper range mentioned above. If the efficiency is independent of the length, the amount of the reactant that undergoes reaction will remain the same. That means the volume of the cylinder (the shape of the reaction cartridge) that contains the reactants is constant regardless of the cylinder height (equal to the wire length since the ignition wire runs

along the center axis of the cylinder). The reduction in the height of the cylinder should be compensated by the increase in the base of the cylinder if the energy efficiency is the same.

The assumption of the equal energy efficiency for different wire lengths is based on the following fact. As long as the stored electrical energy is fixed, the electrical energy expended per unit length by the shorter ignition wire should be larger than that for the longer wire. Thus it can impart more electrical energy per unit length to the surroundings, igniting a larger cross section of the reactants.

The result that illustrates this case is shown in Table 4-3. The table compares the results of two tests using different cylinder shapes to hold the reactants. The height of the first test cylinder (5 cm) is one half that of the second one (10 cm), while the first cylinder's base is twice as large as that of the second one, making their volumes equal. As shown in the table, the extent of the reaction of the mixture placed in the shorter cylinder (cartridge) is about 20% lower than that in the taller cylinder. Under the assumption of the same energy efficiency, the cross section of the reacted mixture of the shorter cylinder would be doubled. But the test result shows that the increase is only 50%. Thus, it is seen that the longer wire length is nearer to the optimized one than the shorter one. The reduction in the wire length from the optimized value would not necessarily accompany an increase in the cross section of the reacted mixture.

TABLE 4-3. EFFECT OF THE GEOMETRIC ARRANGEMENT OF THE REACTANT ON THE ENERGY EFFICIENCY

The mixture contains 16 g of aluminum powder and 16 g of water.

Cross Section of the Mixture (cm ²)	Height of the Mixture (cm)	E _i (kJ)	Percentage of the Mixture Reacted	E _o (kJ)	Ratio of E _o to E _i
3.88	5	4.8	63	150	31
1.98	10	4.8	82	197	41

Figure 4-5 shows the current traces of the exploding wires, 5 and 10 cm long, used to ignite the mixture contained in the two cylindrically shaped reaction cartridges as described above. The current trace for the longer wire is decreasing much more steeply after the peak current, since the rate of the energy dissipation for the longer wire is higher when other conditions are kept constant. Thus the longer wire has the more compressed energy dissipation, and this apparently is effective in igniting the reactants.

Thus far, the ignition of the reaction has occurred in a confined reaction chamber. Also, the chamber, being full of the mixture, contained no empty space. Thus the chemical reaction taking place in the mixture is basically a condensed phase reaction. It was found that the energy efficiency also decreases as the degree of the confinement increases by increasing the thickness of the diaphragm shown in Figure 3-2. Therefore, it can be conjectured that the reaction can proceed further if the confinement condition is released by agitating the reactants in a proper manner.

This conjecture was tested by partitioning the reactants into two compartments, a primary and a secondary reaction chamber, positioned linearly one after the other as seen in Figure 3-3. Only the reactants in the primary chamber are subjected to the electrical pulse. As the reaction proceeds, the pressure increase causes the diaphragm separating the two chambers to rupture, and the reacting material from the primary chamber is injected into the secondary chamber. The reaction products are collected in the collecting chamber attached to the reacting chambers. If all of the reactants that can undergo a full reaction under this scheme were placed in a larger primary chamber (no secondary chamber) and subjected to an electrical pulse of the same magnitude, the reactants would be only partially consumed.

The result of such partitioning is shown in Table 4-4. By this partitioning technique, the energy efficiency has been increased to almost 100. We believe the increase in the reactivity of the two-stage scheme is attributable to the attainment of higher thermal energy during the transfer process, which shakes up the reactants and lets them have more surface contact. Thus, with this technique, more thermal energy is imparted to the reactants in the secondary chamber than would be imparted to them if they were placed in a single, larger chamber as an additional portion. In the conventional one-stage reaction, the confinement impedes increased surface contact among the reacting species, thus limiting the chemical energy production.

EFFECT OF PHYSICAL AND CHEMICAL PROPERTIES OF THE REACTANTS ON THE ENERGY EFFICIENCY

The effect of the physical size and shape of aluminum particles on the reactivity with water is shown in Table 4-5. The reactivity is found to be very sensitive to the

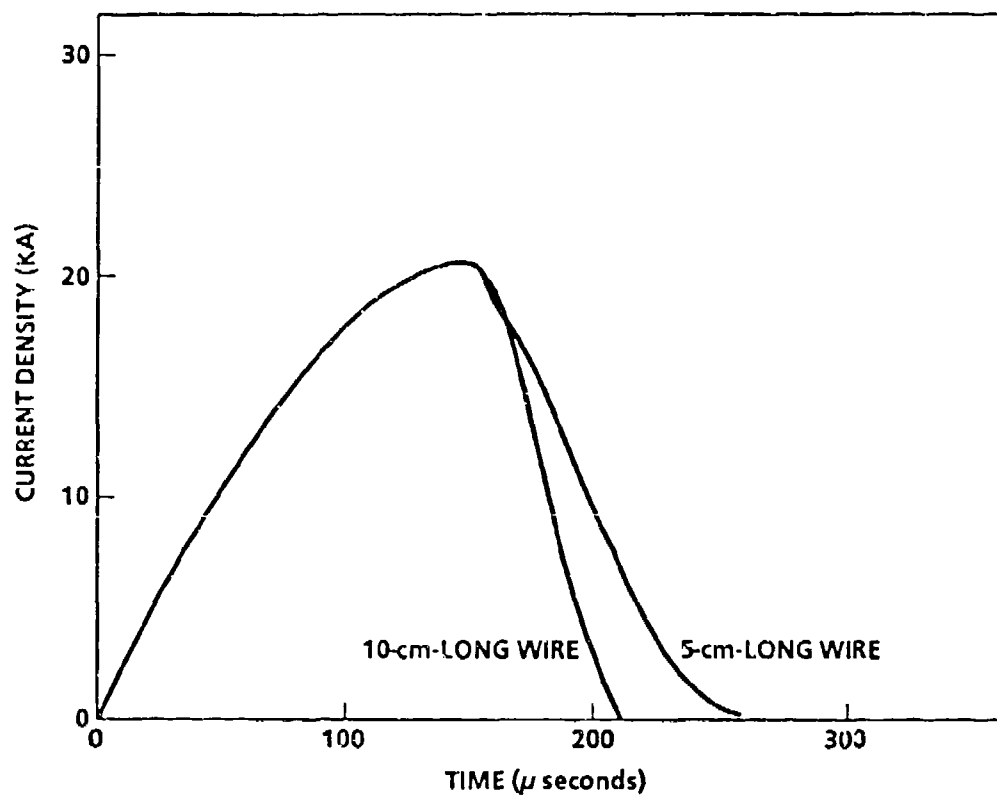


FIGURE 4-5. CURRENT TRACE AS A FUNCTION OF THE LENGTH OF THE IGNITION WIRE

TABLE 4-4. PARTITIONING OF THE REACTANT INTO PRIMARY AND SECONDARY CHAMBERS AND ITS EFFECT ON THE ENERGY EFFICIENCY

Reactant* (g)	E_i (kJ)	Percentage of the Mixture Reacted	E_o (kJ)	E_o/E_i	Energy Output (kJ/g of solid reactant)
32 (P)	4.8	82	197	41	12
20 (P) 10 (S)	3.7	87	195	53	13
21 (P) 11 (S)	4.8	92	221	46	14
32 (P) 10 (S)	4.8	91	287	60	18
38 (P) 26 (S)	6.1	62	298	49	9
42 (P) 22 (S)	6.1	70	336	55	11
38 (P)	6.1	94	268	44	14

* Reactant is a stoichiometric (1:1 weight ratio) mixture of the aluminum particles and water. P and S denote the primary and the secondary chambers, respectively.

TABLE 4-5. EFFECT OF ALUMINUM PARTICLE SIZE AND SHAPE ON THE ENERGY EFFICIENCY

Type, Shape, and Size of Al Particles	Percentage of the Mixture Reacted
Al, nonspherical, $<44 \mu$	>90
Al, nonspherical, $44 - 354 \mu$	<50
Al, spherical, 20μ	<10
Al-3%Li, nonspherical, 20μ	Instant Reaction on Mixing

shape of the particulate. The spherical aluminum powder showed little reactivity with water even when the electrical energy input was increased. The mixture of water and aluminum particulate whose diameter is smaller than $44\ \mu$ can build pressure if it is kept in a confinement after being mixed. Thus, the mixture confined in the reaction chamber has to be activated by the electrical pulse within one hour of its preparation. The reactivity of Al-Li alloy particles with water is so great that they cannot be mixed.

To use the alloy powder as the metal fuel, a method has to be developed in which the powder is mixed right before the electrical pulse application. An attempt was made to dynamically mix the powder and water, which were physically separated by a thin barrier. In this method, double electrical pulses were fed into the reacting system, the first pulse for demolishing the barrier and the next one for the ignition. The difficulty with such a mixing method is the lack of a free space in the reaction chamber. The metal fuel is compacted rather than mixed with water when the first pulse is applied.

If the condition of fast mixing and immediate activation is somewhat relaxed, many mixing methods can be conceived. One of them could be the injection of pressurized water into the metal powder with the provision of an escape route for the trapped air.

A water oxidizer is advantageous over others due to its abundance and safety. But the bonds between its constituent atoms are so strong that a lot of energy must be expended to break them. If some of the water oxidizer is replaced by metal oxides such as copper oxide or iron oxide, the electrical energy necessary to ignite the reactants can be reduced. The results of several tests incorporating copper oxide are summarized in Table 4-6. Obviously, a higher metal oxide percentage reduces the gravimetric energy output of the reactants. However, when 10% of the water was replaced by the metal oxide, the gravimetric density expressed in kJ/g of the solid reactant exceeded 10, while the energy efficiency reached 116. When 25% of the water was replaced by the oxide, the energy efficiency exceeded 200. When this method is employed, the penalty paid in terms of the reduced gravimetric energy density should be carefully weighed against the reduction of the electrical power source.

TABLE 4-6. EFFECT OF ADDING METAL OXIDE TO THE REACTANT ON THE ENERGY EFFICIENCY

Reactants (g)	E_i (kJ)	Percentage of The Mixture Reacted	E_o (kJ)	E_o/E_i	Energy Output (kJ/g of solid reactant)
16 Water 16 Al	4.8	82	197	41	12
15 Water 16.5 Al 6.1 CuO	2.2	100	256	116	11
12 Water 16 Al 17.6 CuO	1.2	88	248	206	7.4
9 Water 9.3 Al 1.3 CuO	2.7	NR*			

* No significant chemical reaction takes place.

The heat of reaction for the Al/CuO reaction is 144 kcal (603 kJ) per mol Al.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

The effectiveness of the pulsed power technique in driving aluminum/water reactions has been studied. The reacting system consists of a mixture of aluminum particles and water in a slurry form with an aluminum wire running through the mixture. The ignition wire should carry the current to near its peak value right before its explosion in order to make the most efficient utilization of the stored electrical energy. This requirement uniquely determines the diameter of the wire for a given stored energy. There is a range of the inductance that helps form an effective pulse shape in driving the reaction.

It was found that the reactivity is very sensitive to the metal particle size and shape. Spherically shaped particles show little reactivity. Particles exceeding $100\ \mu$ also show a reduced reactivity. By employing techniques such as a two-stage reaction, the energy efficiency has been increased to almost 100, one hundred times higher chemical energy output than the electrical energy input. Adding a small amount of metal oxides can further increase the efficiency but, due to the decrease in the energy density, there should be a limit to the amount of added oxides.

For practical applications of the reacting system, it is recommended that the mixing process occur a short time prior to the pulse application to minimize any premature reaction of the mixture. By drawing water at the needed time from the surroundings, an underwater device utilizing this type of reaction does not have to carry water. Also, carrying only the metallic fuel means that the system is very insensitive.

Future work should include the following tasks. First, more accurate dynamic pressure needs to be measured, particularly during the two-stage reaction, to determine the reaction time and the pressure amplitude. Also, a prototype device based on the concept described in this report should be assembled. Using the electric power supply and its related electronics, a compact portable unit can be built. The performance of such a device should be examined carefully and compared with conventional devices.

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